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Title: Calculations for the Scorpius Downstream Transport

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Calculations for the Scorpius Downstream Transport

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May, 2021

Over heating a beam stop can lead to damage, even if the temperature rise is insufficient to melt or dissociate the material.

- **Heating the surface of a beam stop by $\Delta T > 300\text{-}400\,K$ desorbs monolayers of H_2O and other gases.**
  - **H_2O desorption is a concern because it is a source of light ions, e.g., H^+**
  - **H_2O has been shown to be ubiquitous in vacuum systems like our LIAs.**

- **Impact dissociation and ionization of desorbed gas produces positive ions that are accelerated upstream into the beam space-charge potential well.**
  - **Positive ions partially neutralize the electron beam charge.**
  - **Neutralization factor is $f_e = N_i/N_e$**

- **H^+ (protons) can be accelerated far enough upstream that space-charge neutralization is sufficient for the beam to magnetically pinch due to its current.**
  - **Neutralization $f_e > 1/\gamma^2$ is enough to overcome space-charge repulsion and permit pinching.**
  - **The tightly focused beam resulting from this ion focusing effect can damage the material.**

- **This effect has been demonstrated in a number of experiments.**

Expanding the beam to reduce the beam-stop temperature rise can be accomplished by over-focusing with a solenoid.

- We have successfully used this technique to protect the DARHT-II beam stop from overheating by the 17-MeV, 1.7 kA, 2-μs FWHM beam.

- For the Scorpius beam stop, we studied the use of the TS1 solenoid to expand the beam.
  - We used the XTR envelope code and the LSP-S PIC code for this analysis.
  - Beam parameters at the accelerator exit were determined from simulations of transport through the full Scorpius LIA.
  - The magnetic field was calculated from the XTR solenoid model with parameters fit to field simulations based on the present TS1 design.
  - Axial locations were based on the present DST design.

Beam expansion using TS-1 can be simulated with the XTR envelope code.

- **The envelope equations have been derived for an azimuthally symmetric current with arbitrary radial distribution.**
  - XTR solves for $R_{env} = 2^{1/2} R_{rms}$
  - Valid for self-similar variations of beam size.
  - Useful for impulsive beam heating with pulse times much shorter than thermal diffusion times
- **XTR is our “go-to” envelope code for intense relativistic beam transport with solenoidal focusing.**
- **Envelope tutorial: LA-UR-19-28456**

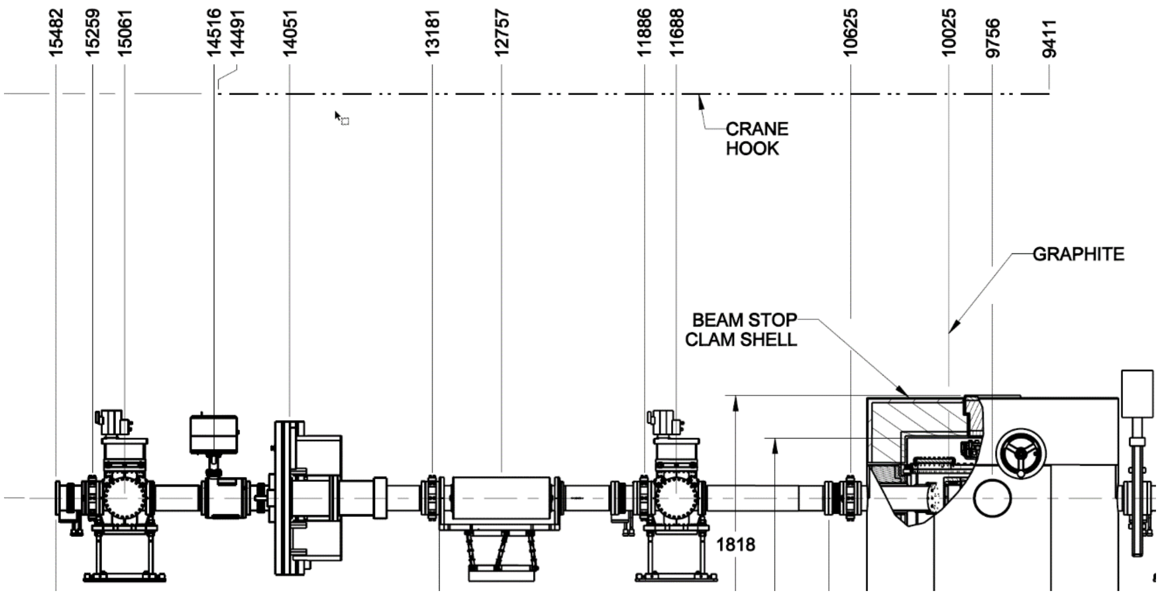
Radial beam current distribution was simulated with LSP particle-in-cell (PIC) code.

- Relativistic beams are dominated by transverse forces.
  - Results of PIC simulations with a thin slice agree with full 3D simulations.

- The beam-slice algorithm for LSP enables cathode-to-target PIC simulations in finite wall-clock time on a Win10 workstation.
  - Fastest Simulations: 1D cylindrical geometry
  - Best Resolution: 2D Cartesian geometry
  - 1D and 2D results agree for azimuthally symmetric beams launched straight down the axis.

- For these initial estimates, I traded off resolution for speed, using a coarsely-zoned Cartesian geometry.

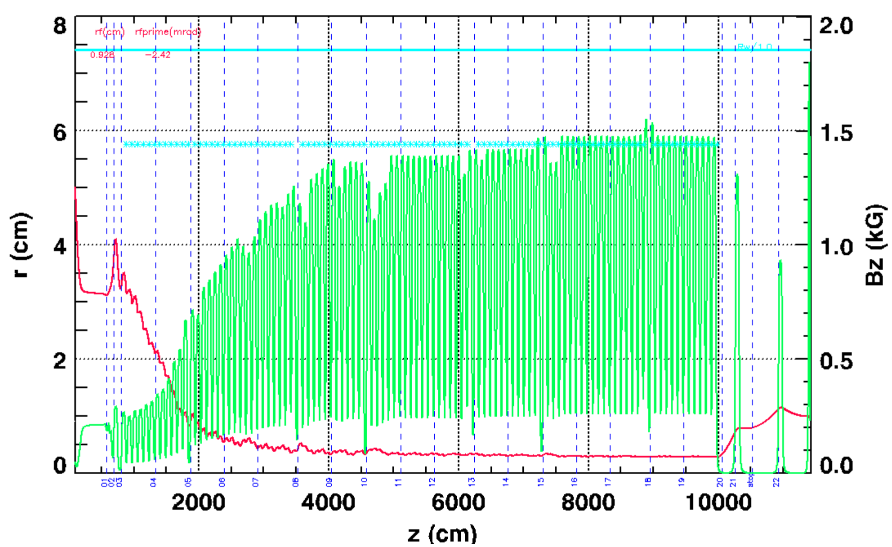
Locations for the DST simulations were taken from Juan's latest (?) spreadsheet.

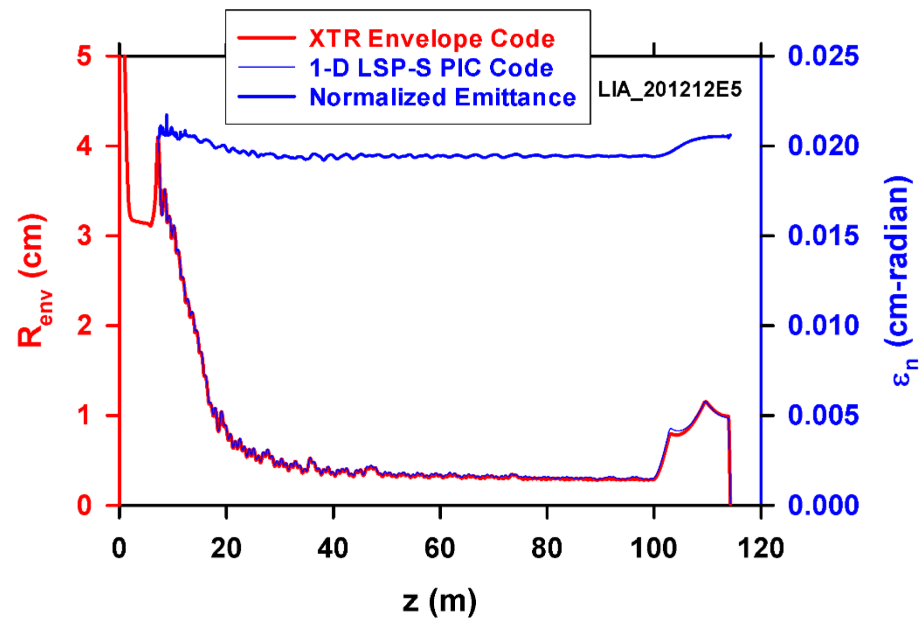


			Pump Port	99448.38		
		6	Cell Magnet	99840.76		**DST Coordinates**
			AK Gap	100214.20	RF Gate Valve	15482
DST Region1	BPM 22		BPM	100666.17		15259.00
			Pump Port	100864.17		15061.00
			Debris Blocker	101874.17		14051.00
			BPM	102745.17		13180.00
DST Region 2			Transport Solenoid	103168.17		12757.00
	BPM 23		BPM	104004.17		11921.00
			Pump Port	104202.17		11723.00
DST Region 3	BPM 24		BPM	105265.17		10660.00
			Beam Stop Graphite Face	105865.17	RF Gate Valve	10060.00
DST	BPM 25		BPM	107302.17		8623.00

For this investigation I used the beam transported by a nominal tune that is also being used to assess beam stability.

- This tune was designed with XTR to match a beam with initial conditions from diode simulations with the TRAK e-gun code.
- An envelope-stable, matched beam is transported and accelerated through the LIA with this tune.
- LSP-Slice predicts no emittance growth for this tune.
- LAMDA simulations predict that maximum B-field less than 1.5 kG will suppress BBU growth to less than on DARHT-I .
- The DST is tuned for optimally-sized waist (R ≈ 1cm) entering the final focus solenoid.





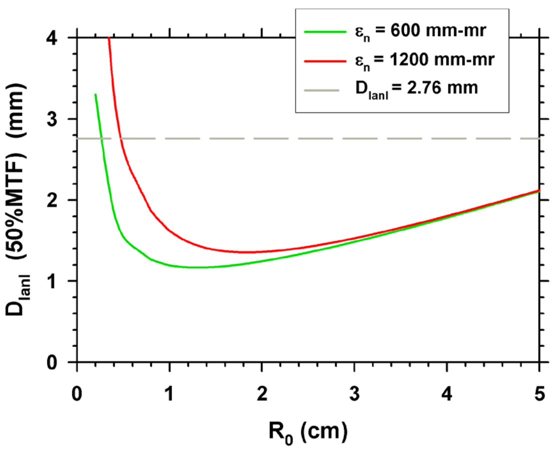
Several physical effects contribute to the spot size, which can be minimized by tuning for optimum beam size entering the final focus

$$r_{spot}^2 = \underbrace{\left(\frac{\varepsilon_n f}{\beta\gamma R_0}\right)^2}_{\text{Fundamental Minimum}} + \underbrace{\sum R_{aberrations}^2}_{\text{Focusing}} + \underbrace{\sum R_{beam-target}^2}_{\text{Ion Defocusing}}$$

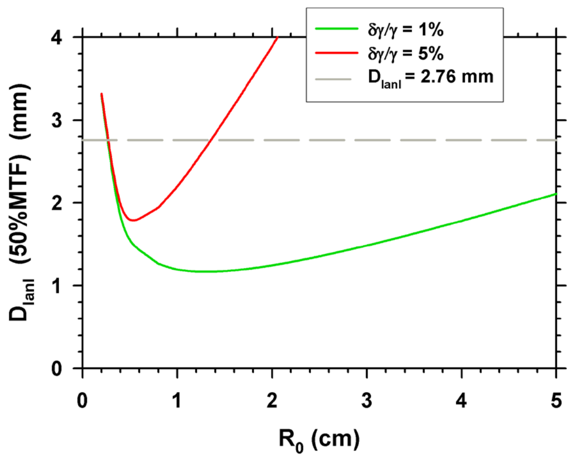
Beam parameters that are under some degree of control (emittance, energy spread, and beam motion) all contribute to an enlarged spot size.

$$r_{spot}^2 = \left(\frac{\varepsilon_n f}{\beta\gamma R_0}\right)^2 + \left(\frac{2\delta\gamma}{\gamma} R_0\right)^2 + \left(C_S R_0^3\right)^2 + \left(\delta_{ions}\right)^2$$

Influence of emittance on optimum DST tune



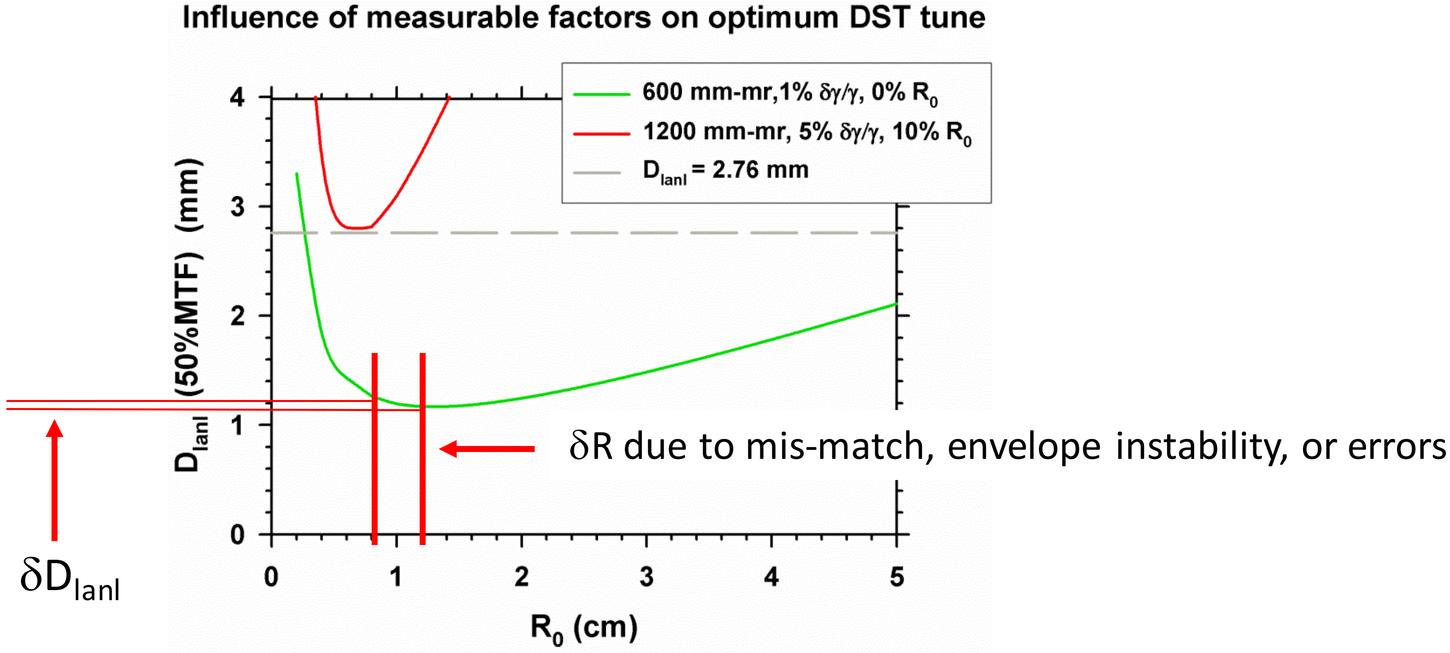
Influence of energy spread on optimum DST tune



Beam motion resulting from instabilities further blurs the time-integrated spot:

$$r_{blurred} = r_{spot}\,(1+0.01\Delta R\%)$$

The spot size is relatively insensitive to errors in tuning for the optimum R_0 entering the final focus solenoid.



- Spot size can be minimized by tuning the downstream transport for the optimum R_0.
- Minimum spot achieved when each contributing effect is minimized.
- Beam motion blur due to instabilities does not change optimum R_0.
- Diagnostics required to establish optimum R_0 are emittance, energy and high-frequency motion, at least.

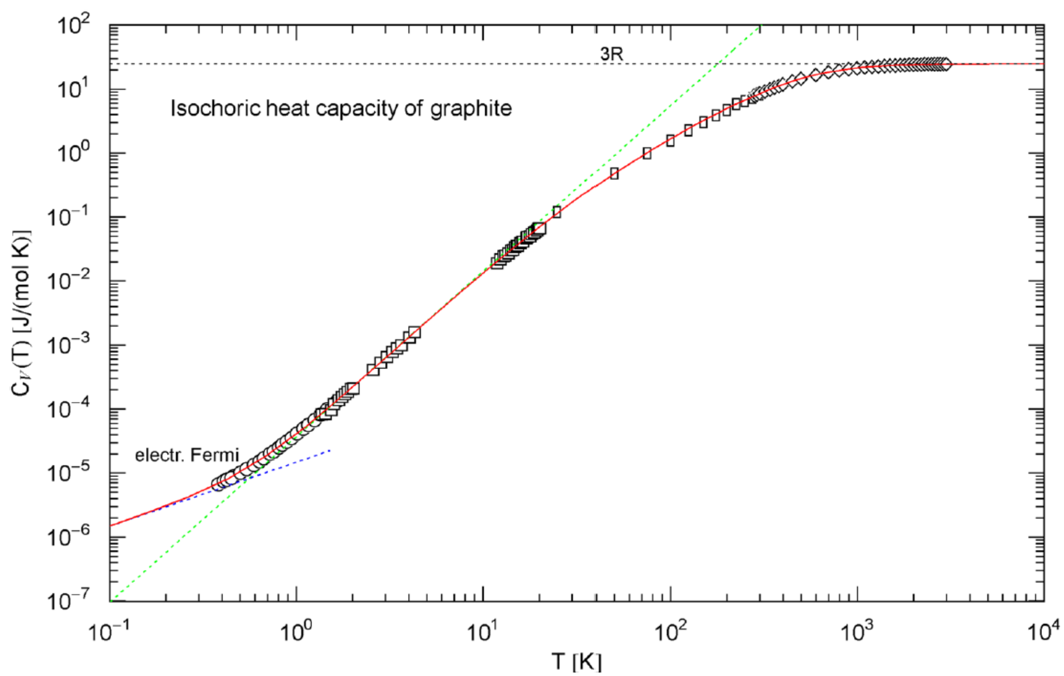
One can use a conservative estimate of the heating to bound the design.

- **Impulsive beam heating of a target surface during a time much less than thermal-diffusion or hydro-expansion times can be estimated from:**

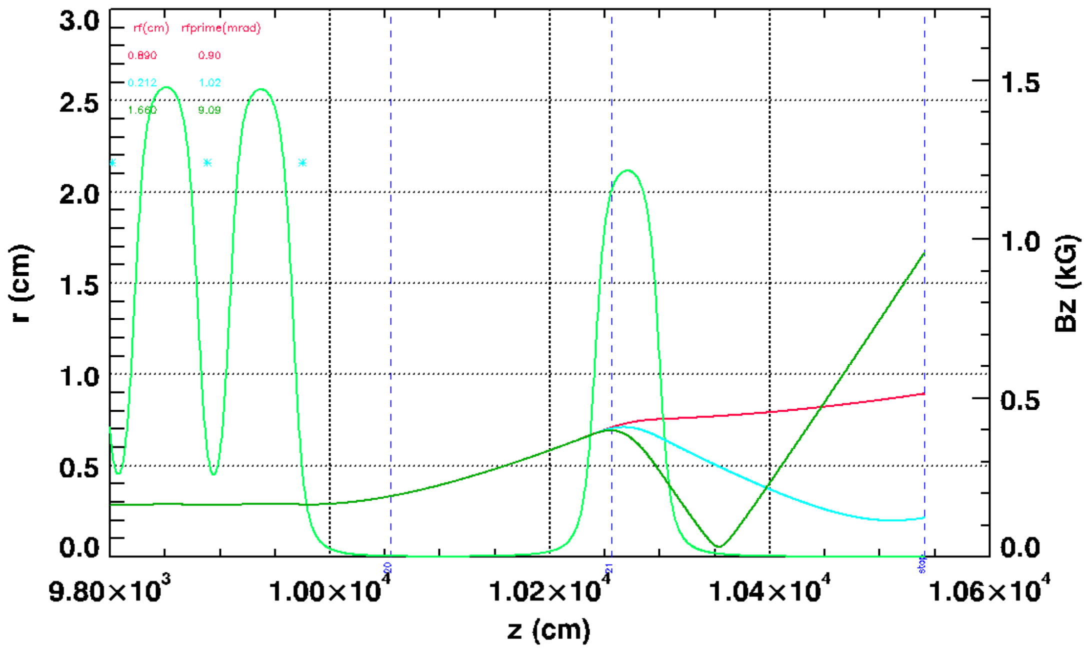
- **$\delta T = S_c$ (MeV-cm^2/g) x J_{max}(kA/cm^2) x dt(ns) / c_V(J/g/K)**
  - **Collisional stopping power; S_c(22.4 MeV) = 1.826 MeV/(g/cm^2)**
  - **Isochoric specific heat; c_V(290K) = 0.644 J/g-K**
    - **for T > 290K, c_V > 0.644 J/g-K, so using this value is a conservative (over-estimate) of heating.**
  - **PIC code simulations suggest current distributions between uniform and Gaussian:**
    - **Uniform: $J_{max} = I_b/pR_{env}^2$**
    - **Gaussian: $J_{max} = I_b/pR_{rms}^2 = 2 \times J_{max}$ (Uniform)**
    - **These estimates bound the problem**

Comments on specific heat, and its influence on beam-stop heating estimates.

- Tabulated specific heat is almost always isobaric; c_P
- Isochoric specific heat is always less than isobaric, $c_V = c_P - VT\alpha^2/\beta$
  - β = compressibility, α = coefficient of thermal expansion
- => using c_P rather than c_V underestimates temperature increase, especially since c_P increases with temperature more than c_V
- Using c_V at T = 300K overestimates the temperature increase, so is a conservative approach to design: c_V(290K) = 0.644 J/gK for graphite



Using TS1 as the cruncher requires a solenoid capable of producing about 3-kG peak field.



Surface Heating

- 22.4 MeV
- 1.45 kA
- 4- pulses
- 80ns FWHM each
- Uniform Distribution
  - $J_{max}=I_b/\pi R_{env}^2$
- Gaussian Distribution
  - $J_{max}=I_b/\pi R_{rms}^2$

- (R_{env} = 1.414 R_{rms})

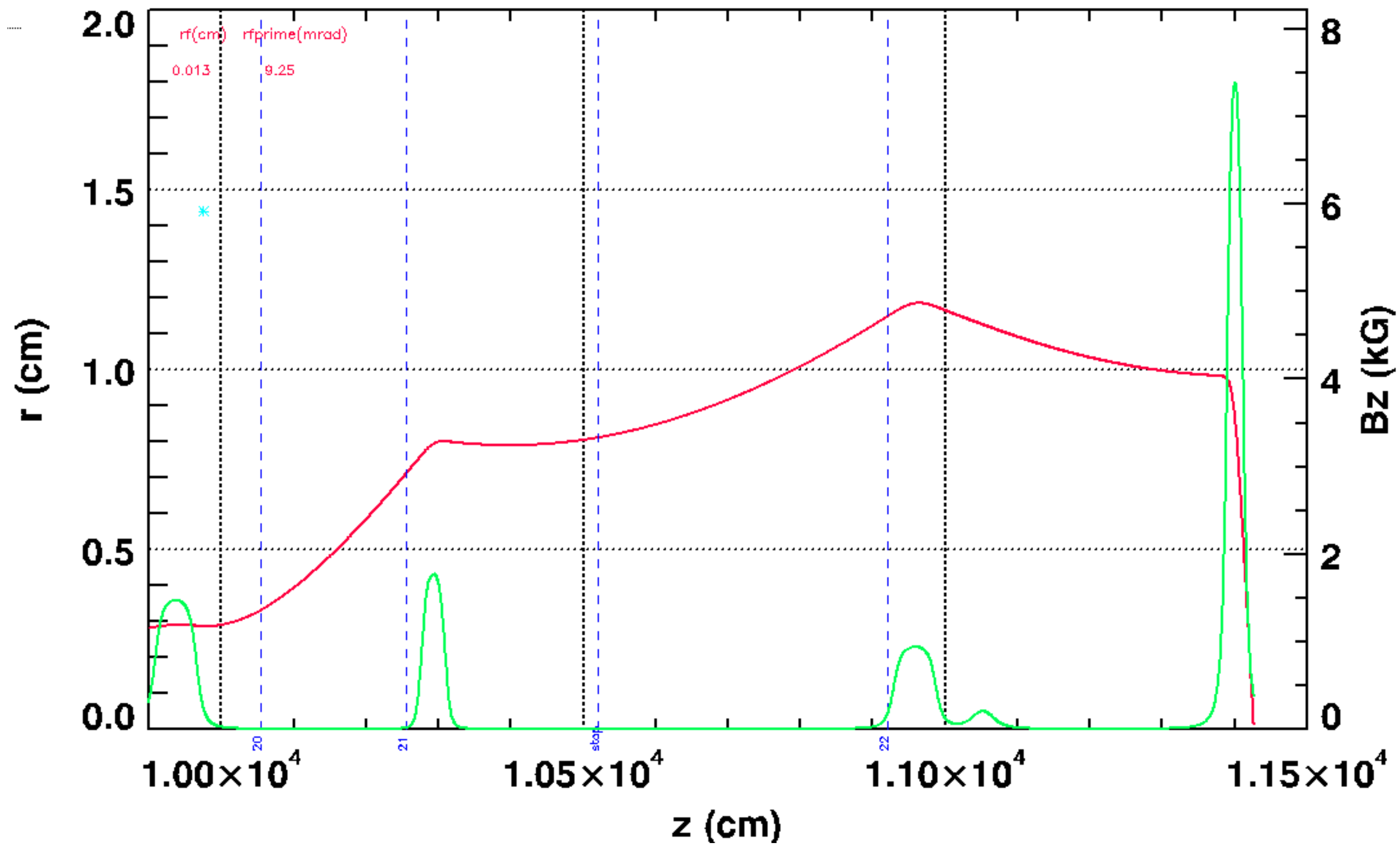
color	B_{max} kG	R_{env} cm	R_{rms} cm	dT_U K	dT_G K	comment
Red	1.22	0.89	0.63	530	1060	Nominal Tune
Cyan	1.95	0.21	0.15			4-Layer limit ?
Green	2.89	1.66	1.17	152	304	Safe

The new DARHT-II S2 solenoid can be used instead of the Scorpius 4-layer solenoid for transport and cruncher (TS1).

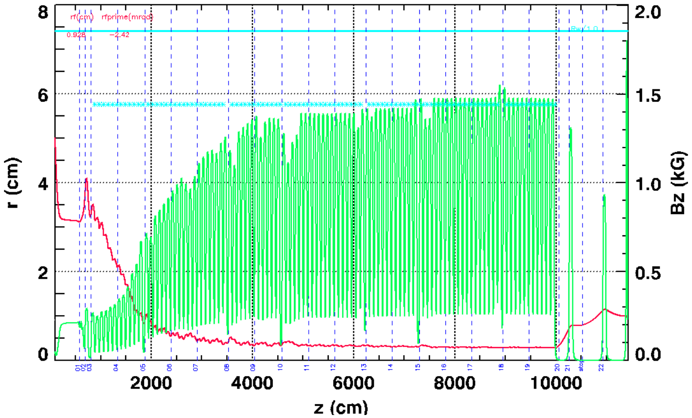
- **Bare Scorpius 4-layer solenoid (godiva4)**
  - [Leff(cm), Reff(cm), G/A, "n", alpha]
  - [58.13437,10.80557,4.61102,2.01033,0]: PerMag model
  - $1/f$ =Integral[$k_\beta{}^2$] {z,-∞,+∞} ; $k_\beta = B_z(\text{kG})/3.4\beta\gamma$
  - Optimized transport for 1.2 kG (264A) & KE=22.4, f = 306 cm
    - Cs1 =0.0006165/cm^2
  - Crunching with 3-kG (651A) & KE=22.4 , f = 54 cm

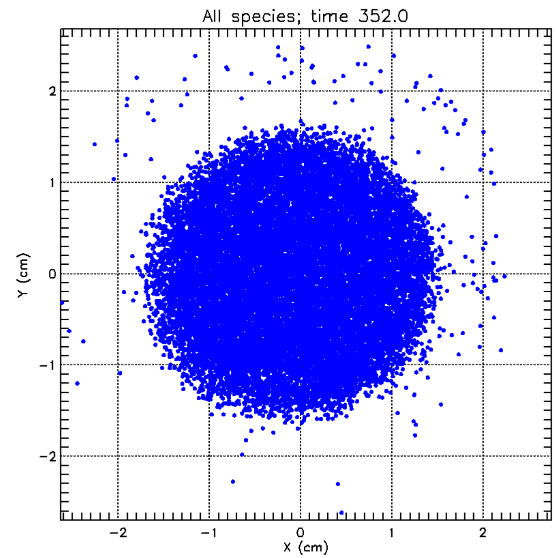
- **DARHT-II S2 solenoid (curly)**
  - [31.879,8.18079,15.07,2.83795,0]: Barlow map
  - Optimized transport for 1.72 kG (114A) & KE=22.4, f = 302 cm
    - Cs1 = 0.001753/cm^2
  - Crunching with 4.1 kG (270A) & KE=22.4, f = 54 cm

The DST can be optimized to enter FF at Renv ∝ 1 cm using DARHT S2 at TS1 and the DML solenoid producing 200 G.

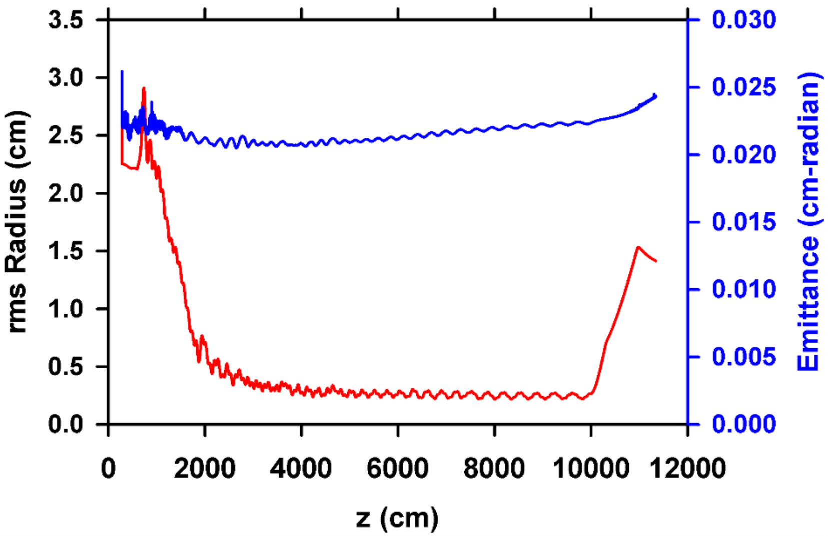


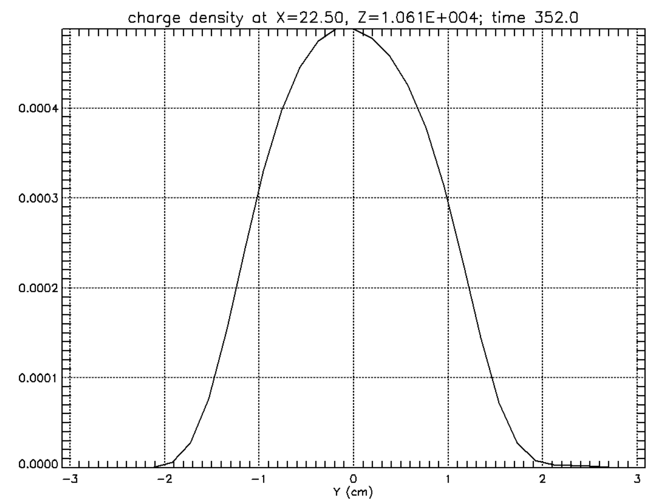
The beam distribution near the beam-stop was obtained from PIC code simulations of transport and acceleration through the LIA.





The tu ne transports a well-matched beam with almost no oscillations at high energy.



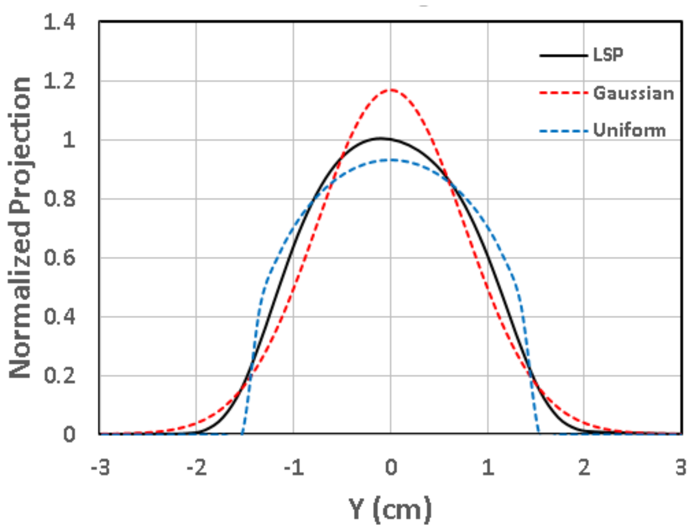


For this simulation the beam was slightly mismatched causing weak envelope oscillations and emittance growth.

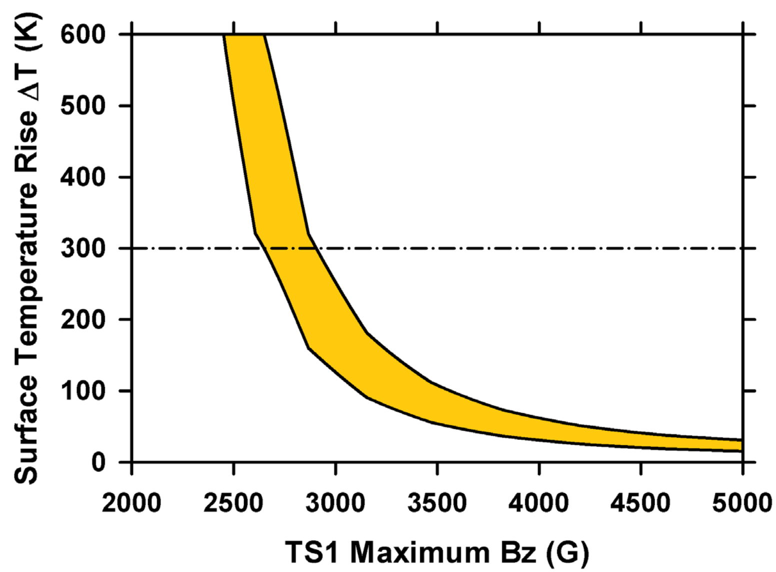
Projection onto Y axis

Rrms = 1.05 cm
en = 0.023 cm-radian

PIC simulations suggest that the maximum current density lies between that for Uniform and Gaussian distributions..



The peak current density is more than for a uniform beam of the same rms size carrying the same current, but more than for a Gaussian beam.



This suggests that the temperature rise will be in a range bounded by uniform and Gaussian distributions.

TS1 maximum field should be sufficient to prevent impulsive overheating.

Conclusions:

- **Initial estimates suggest that using TS1 to expand the beam in order not to overheat the beam-stop will require a peak focusing field of 3 kG or more using a bare Scorpius 4-layer solenoid.**
- **The new DARHT-II S2 cruncher design can be used for TS1.**
  - **It's a shorter magnet (about ½ L), so equivalent focusing field for the same beam expansion is 4.1 kG.**
- **LSP PIC code simulations show that the beam current density radial profile evolves from uniform at the diode to convex at the LIA exit.**
  - **Current density is less centralized than Gaussian, which might be used as a limiting case for heating.**
- **The DST tune with S2 and energized DML can be optimized to enter the final focus at a waist with R_{env} about 1 cm for minimum spot size.**

Future Directions:

- Corroborate PIC code current distribution with real data from DARHT-I imaging.
- Corroborate impulsive surface-temperature rise with thermodynamic codes.
  - Source energy deposition with Monte Carlo simulations based on Gaussian worst-case distribution (Cyltran, MCNP, Penelope, EGS, GEANT, etc.)
  - Include temperature dependent material properties (heat capacity, thermal conduction, etc.)
- Perform higher resolution PIC simulations.
  - Include beam expansion using TS1
  - Corroborate PIC code current distribution with real data from DARHT-I imaging.